PTTI Applications at the Limits of GPS

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Abstract

Canadian plans for precise time and time interval services are examined in the light of GPS capabilities developed for geodesy. We present our experience in establishing and operating a geodetic type GPS station in a time laboratory setting, and show sub-nanosecond residuals for time transfer between geodetic sites.

We present our approach to establishing realistic standard uncertainties for short-term frequency calibration services over time intervals of hours, and for longer-term frequency dissemination at better than the 10^{-15} level of accuracy.

The state-of-the-art for applying GPS signals to geodesy is more advanced in some ways than is the common practice by national time and frequency laboratories for applying GPS signals to PTTI work. The Geodetic Survey of Canada's positioning capabilities have benefitted greatly from the application of GPS techniques [1], which include GPS Inferred Positioning System (GIPSY) software developed at the Jet Propulsion Laboratory, with a capability for sub-nanosecond clock synchronization [2], [3]. Currently, GPS techniques for time transfer between national time laboratories have not exploited the more advanced global geodetic capabilities.

In national time laboratories, common practice has been to use single-channel C/A code receivers in the common-view mode where 13 minute tracks (about 40 per day) are taken on its regional tracking schedule. The tracking schedule is issued for each region by the International Bureau of Weights and Measures (BIPM), and with a delay of several weeks the common-view differences are post-processed (with the measured ionospheric corrections, when available) using the precise ephemerides determined for geodesy. One major refinement to this process is possible by using

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GPS receivers which can make comparisons with the GPS carrier phase, and use this information for interlaboratory frequency comparisons. Geodetic receivers can do this, producing significantly higher precision measurements than the usual timing receivers. Geodetic receiver networks also track signals simultaneously from multiple satellites (up to 8) to obtain 10-20 times more data from each station than is specified in the BIPM tracking schedule. Geodetic receivers track C/A code, carrier phase, and P code on the L1 and L2 frequencies (when Anti-Spoofing, or AS, is off and the P code is transmitted), measuring them all with respect to the receiver clock, locked to the station's frequency reference. Ionospheric corrections are measured for all satellite tracks from the difference in arrival time of the L1 and L2 signals, determined from L1 and L2 P-code measurements (AS off) or from cross-correlation of the L1 and L2 signals (AS on). Tropospheric corrections are also modelled for each station [2]. Daily satellite orbit solutions, based on these observations from around the globe, determine the space coordinates of the GPS receivers at the level of about 3 cm or 100 ps; and benefit from station frequency references derived from modern masers.

Despite remarkably good time residuals of well under a nanosecond [2], [3] reported using these techniques, they have not yet been widely embraced by national time laboratories. Subnanosecond timing precision might lead to improved short-term accuracy of interlaboratory frequency comparisons and facilitate the use of the next generation of primary frequency standards. Benefits would also accrue for remote frequency calibrations of hydrogen masers (particularly free-running hydrogen masers), or frequency calibrations of compact hydrogen masers, or calibrations of cryogenic superconducting and/or dielectric frequency standards, or perhaps even providing short-term calibration commensurate with the 10^{-13} 1000s-stability of the best crystal oscillators [5].

In Canada, the geodetic spatial reference system is the responsibility of the Geodetic Survey Division (GSD) of the Federal Government's Department of Natural Resources (NR Can), and the time reference is the responsibility of the Time and Frequency Standards Group of the National Research Council of Canada (NRC). The two organizations have begun preliminary work on evaluating the possibilities and benefits of collaboration. This paper will focus on the precise time and time interval aspects, and possible PTTI applications.

The Global Geodetic GPS Network

The International Association of Geodesy formally established the International GPS Service for Geodynamics (IGS) in 1993. It started operations in 1994, with over 40 participating agencies from more than 20 countries. Over 50 continuously operating stations are now collecting and exchanging data (mostly using Rogue GPS receivers), with many more planned. Of these stations, some use a hydrogen maser frequency reference; and of these some take part in VLBI observations for geodesy and time transfer. The IGS data are archived in three Global Data Centres, and analyzed by seven Analysis Centres which forward their results to the Global Data Centres for archiving and on-line access.

The Geodetic Survey of Canada operates one of these Analysis Centres, and the data analyses reported here are drawn from their routine processing [1]. The daily routine analysis is based on the data from about 24 globally distributed GPS tracking stations (Figure 1). The data from each station, sampled at 30 s intervals, are validated to monitor the receiver clock and tracking including

cycle slip detection), code multipath and ionospheric activity levels, and to compute differential satellite range corrections. One GPS receiver with a hydrogen maser frequency reference is used as a master reference clock, and other stations' clocks are reported with respect to this master clock. GIPSY II software uses carrier phase and pseudo-range measurements to generate, from each day's data, precise GPS satellite ephemerides, satellite and station clock corrections, Earth orientation parameters (EOP), station coordinate corrections and satellite orbit predictions for the next 24 hour period. The full solutions are then used for geodetic positioning, and for the station clock intercomparisons.

GSD processes each day's data independently, without overlaps (unlike other Analysis Centres), using the previous day's predictions as only the initial estimates for satellite orbits. Comparisons of the precise orbits from different Analysis Centres show RMS differences of around 20 cm [4]. Station residuals, on 7.5 min observations, show RMS deviations typically under 1 m for range, 1 cm for phase and less than 300 ps between the receiver clocks of two stations with hydrogen maser frequency standards. The repeatability of the daily averages for the station coordinates is typically 1 to 2 cm. GSD uses AS range bias modelling which shows station and satellite dependences.

The small variations in mean space coordinates mainly reflect *differentials* in reception time, and it cannot be expected that the time coordinate would be as stable on average, since common-mode delays which affect all satellites (and which can largely cancel for the space coordinates) will be included with the station clock in the solutions. The time variances of systematic errors in tropospheric delay variations, uncorrected ionospheric delay variations, multipath pulling systematics, temperature related variations of delay in antennas, cables and receivers; variations in receiver timing due to amplitude variation of the 5 MHz reference, or the 5 MHz reference's cable delay variation all add to the variances of the two station clocks (particularly small for masers) filtered by the whole adjustment process, and warrant careful study at better than the 300 ps level of precision exhibited by the station clock residuals.

Another concern might be that the clock residuals could be deceptively low: that the fitting process is so optimized that the effective bandwidth for clock variations is smaller than we believe. However, in the work presented here, the effective bandwidth of the solutions every 7.5 minutes allows for white phase noise on the receiver clocks of up to 1 ms. This allows the solution to cope with receiver clock resets. The station clock solutions are normally more than 10^7 times smoother than this, and show Allan deviations at 7.5 minutes as small as 3.7×10^{-14}. The broad bandwidth for the station clocks is confirmed in that known clock anomalies are quickly reproduced in time intercomparisons by this method. Independent clock and baseline comparisons between several IGS stations are made by VLBI, and are reassuring [2], [3]. Other independent techniques such as two-way time transfer for time synchronization and frequency calibration will also be used for comparison. Techniques for measuring systematic time delay effects, and where possible correcting their causes, are also planned.

GPS Station at NRC

For the GPS station at NRC, both ground level and rooftop antenna locations were evaluated for multipath and radio interference, and the convenient rooftop location was found more suitable.

The ground level site (the two-way time transfer antenna compound) would also require continuous monitoring of the loop delay ($1.2\mu s$). Three matched triax lines and three matched coax lines were installed, cut to minimize phase perturbations (length a multiple of $\lambda/4$ or 50 ns) for the 5 MHz reference from the maser distribution amplifiers. The three lines permit individual cable delays to be determined. Two Turborogue SNR-8000 receivers were installed to provide redundancy and a capability for evaluating possible systematic effects. For the results presented here, one antenna fed both receivers through a microwave splitter. When the receivers are fed from the same maser, this zero baseline setup shows periods when the clock solution differences are well under 50 ps, although occasional day-to-day variations of 100 ps have been observed. To monitor the receivers clocks and to recover absolute timing, the 1 pps outputs of the two receivers are measured each hour with respect to a 1 pps derived from the maser.

The receivers' 5 MHz frequency reference is supplied by the NRC-built hydrogen maser H4, a low-flux maser with a fluoroplast F-10 coated bulb, operated with cavity autotuning. Its average drift rate is less than 3×10^{-17} per day. The rest of the NRC ensemble consists of two other masers, three NRC-built high-stability primary cesium clocks ($\sigma_y(\tau) \leq \times 10^{-12}/\tau^{1/2}$ out to $\tau = 10^5$ seconds) and two commercial cesium clocks (HP5071A). The other masers are H3: similar to H4, but with a FEP-120 Teflon bulb coating, and an average drift rate of 3×10^{-16} per day, and H1: a free-running NRC-built maser which has been operating since 1967. High-resolution (0.2 ps)phase measurements between clocks of the ensemble are used in an algorithm for generating the ensemble time scale, optimized for stability over several days. The stabilities of all the ensemble clocks are monitored routinely. The Allan deviation attributed to H4 is typically less than 2×10^{-15} over periods of 1-10 days. Thus time transfer, between NRC and other laboratories with similar masers, could reliably measure time transfer instability of a few hundred ps over 24 hours or less; but for investigating the longer term stability limit of GPS time transfer, even the best masers' stability will not suffice and comparisons with other techniques such as two-way time transfer will have to be employed.

Operational Experience

The long-term behaviour of the two Turborogue receivers over the past year has given excellent time residuals, as will be shown below. They have been integrated into the NRC time laboratory operations with only minor problems. The receiver 1 pps outputs have exhibited two types reset, which are somewhat inconvenient. The most common is the receiver software reset, where the receiver software resets its time by n cycles of the analog-to-digital converter clock (48.885 ns at the 20.456 MHz ADC clock frequency) - often by several microseconds - without affecting the coherence of the 5 MHz to 20.456 MHz synthesis. These 1 pps resets present a processing problem only, and when resolved do not affect the precise time and frequency intercomparisons. The rarer type of power-down reset does affect the coherence of the ADC clock synthesis, altering the state of the receiver's synthesizer with respect to the station's 1 PPS. Thus resets after a receiver lock-up (e.g. lightning strike), or after cabling changes or following operator "finger trouble" need to be measured carefully, with respect to the time laboratory's UTC(k). Neither type of reset presents any technical difficulty for a time laboratory, where differences between 1 pps signals are measured and logged automatically.

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The receiver GPS data sampling rate is 30 s (C/A pseudorange, C/A phase, and P2-P1 differential delay, by cross-correlation with AS, or P1 and P2 pseudo-ranges and phases with AS off), and the data is extracted regularly by GSD. GPS data from about 24 IGS sites were used in GIPSY II processing of each 24 hour period, to determine precise GPS ephemerides, Earth orientation parameters and daily station mean coordinates. Station coordinate solutions provide daily mean positions in the ITRF (ITRF92). The daily solutions also provide, in 7.5 minute intervals, receiver clock differences with respect to the reference station, and each station's tropospheric corrections. The receiver clock differences are evaluated allowing for a wide bandwidth white phase noise of 1 ms, and have no further smoothing. No data overlap is used from one day to the next, except that the initial orbit estimates are extrapolated from the precise ephemerides of the previous day's solution. The independence of each day's solution, and its clock intercomparisons, can be used to simplify our preliminary analysis of the frequency stability of this powerful method of clock intercomparisons.

Stability

Operationally, geodesy can tolerate occasional receiver clock resets (of the two kinds discussed above) as well as receiver clock variations in frequency which are undesirable for PTTI stability analysis. For our initial stability analyses, we select periods (of up to several weeks) that are largely free from the unmistakable signatures of these perturbations, and apply the classical techniques of stability analysis. There are other good techniques for examining the stability of the clock difference solutions, such as observing the time residuals on closure checks from solutions over different groups of stations [2] - but we prefer the standard method for quantifying and presenting the method's stability for frequency transfer.

Figures 2 through 6 show receiver clock differences between maser-equipped stations for 20 consecutive daily global solutions, starting at 1994-10-25 00:00 UTC. Figure 2 shows the clock difference for this period along the shortest baseline (200 km), between the NRC time laboratory in Ottawa and the Algonquin Park observatory. In Figure 2, the rapid change in frequency at the end of day 4, of 23×10^{-14}, is associated with a large temperature excursion in the Algonquin maser room, which was fixed on day 7. The rapid response of the solution is noteworthy, and confirms the broad bandwidth allowed by the solution.

Figure 3 shows the maser comparisons between NRC and Goldstone (CA). Figure 4 shows the maser comaprisons between NRC and Madrid (Spain). These are long baselines (4×10^3 and 6×10^3 km), but the stations still have common view satellites in the global solutions. In Figure 5 is plotted a maser intercomparison with a longer baseline (1.7×10^4 km) between NRC and Tidbinbilla (Australia) which have no common view satellites. Figure 6 shows an intermediate case (10^4 km), the difference between the Figures 3 and 4, a comparison between Goldstone and Madrid.

The performance is strikingly good. The daily solutions are not forced to smooth day-to-day maser comparisons, and have to re-solve for the carrier phases from one day to the next. Nonetheless on many days only small discontinuities can be seen between solutions. The largest discontinuities are for the end of days 16 and 18, and are clearly associated with the NRC station bias. Within each day's solution, the maser comparisons are even more stable. For the smoothest comparison,

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Figure 3, the Allan deviation $\sigma_y(\tau = 450s)$ is 1.9×10^{-13}, and 3.7×10^{-14} if the effects of the discontinuities are removed from the analysis. Clearly the effects of systematic uncertainties will be more important for real applications than this level of the solutions' stability. One example of such systematics can be seen in Figure 4, where there is a $\pm 10^{-13}$ short-term frequency variation.

Earlier Algonquin to NRC comparisons are shown in greater detail in Figure 7. The magnitude of the time discontinuities between daily solutions are emphasized in the Figure, and can be used to determine the RMS residual of the clock comparisons at each 00:00 UTC. In the absence of any uncertainty in the solutions, one day's solution should extrapolate (forward in time) to the same clock difference as the next day's solution (extrapolated backwards in time). Since the daily solutions are independent, the time offset in the solutions should average to $\sqrt{2}$ times the residual. Thus the end-point residual can be determined from the RMS average time offset (divided by $\sqrt{2}$). The estimate does not include the full long-term effects of time-dependent variation of the satellite orbits, the station equipment and the atmosphere, which must be accounted for in any estimate of the frequency-transfer stability, however it does account for these effects acting on successive daily solutions, including the redetermination of the carrier phases. Figure 8 shows a histogram of the time discontinuities between NRC's maser and masers at five other stations (Algonquin, Yellowknife, Goldstone, Madrid and Tidbinbilla) for the 20 day period shown in Figures 2-6. The RMS residual is 880 ps, but appears to have outliers from a central peak, which has an RMS of 310 ps.

The zenith tropospheric correction solutions, which are smoothed for each site with a 33 ps/$\sqrt{hour}$ random-walk, for this 20-day period show an Allan deviation of $\sigma_y(\tau = 1\text{day}) = 1.2 \times 10^{-15}$ for the NRC-Algonquin link and up to twice this for the longer baselines. For the results presented here, these small corrections have been applied; for other methods it presents useful insight into one term in the time transfer error budget.

The independence of each day's processing can also be used to determine an Allan deviation from each day's average frequency: $(2M - 1)^{-1} \sum_{i=1}^{M}(Y_{i+1} - Y_i)^2$. The results of this Allan deviation, comparing the NRC maser to remote clocks via the geodetic network's clock solution clearly shows clock noise for some stations: For St. John's (Newfoundland), using a Rb clock, $\sigma_y(\tau = 1\text{day}) = 7.7 \times 10^{-13}$; for Penticton (BC), using a cesium clock, $\sigma_y(\tau = 1\text{day}) = 3.6 \times 10^{-14}$; for Algonquin, using a maser with a misbehaving maser room thermostat, $\sigma_y(\tau = 1\text{day}) = 3.8 \times 10^{-14}$; for the remaining four stations equipped with masers, at Yellowknife $\sigma_y(\tau = 1\text{day}) = 1.1 \times 10^{-14}$; at Tidbinbilla $\sigma_y(\tau = 1\text{day}) = 7.0 \times 10^{-15}$; at Madrid $\sigma_y(\tau = 1\text{day}) = 5.0 \times 10^{-15}$ and at Goldstone $\sigma_y(\tau = 1\text{day}) = 4.9 \times 10^{-15}$.

These results are quite encouraging, but further work is required to study possible systematic time and frequency biases present. The short-term stability of frequency transfer also warrants further study. The results shown in the NRC-Madrid comparison (bottom graph in Figure 3) show a residual double-hump structure, within each day's solution, which is not likely due to the intrinsic behaviour of the Madrid maser and could be associated with GPS satellite constellation geometry. Clearly this behaviour could generate biases on hour-long frequency calibrations by GPS which could be up to $\pm 10^{-13}$. The long-term statistics of the comparisons, including the time offsets between daily solutions, need to be considered and compared with other high-accuracy methods such as two-way time transfer. Post-processed frequency and time dissemination within Canada will benefit if these questions can be addressed for periods of 10^3 to 10^4 seconds. One can imagine

calibration services that provide traceable frequency calibrations for crystal oscillators at accuracy levels of 10^{-12} and better. If the longer term accuracy (for time intervals longer than one day) can also be established, the GPS geodetic-style time transfer might be helpful in comparing the next generation of high-accuracy frequency standards [6], particularly on baselines where two-way time transfer is more difficult. To establish the random component of the standard uncertainty associated with this type of frequency transfer, we would like to apply the techniques we have developed for standard power-law noise models [6]. These techniques can be applied to the continuous clock solutions within the day, but require further development to be applied for longer time periods. The frequency transfer capabilities of operational GPS systems, developed for geodesy, appears to be a strong candidate both for interlaboratory frequency comparisons and for frequency dissemination applications.

Acknowledgements

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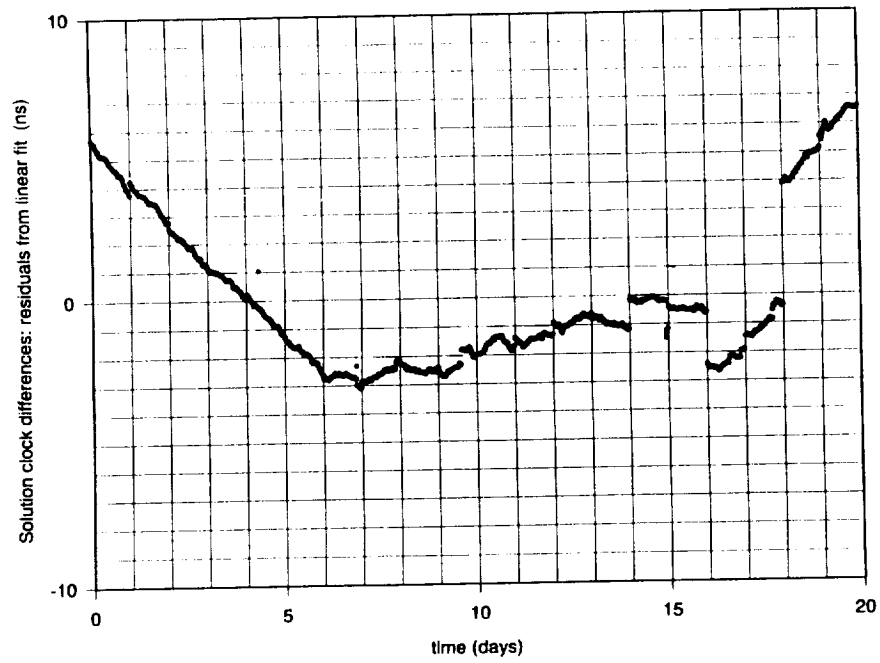
Figure 1. Map showing locations of existing and planned GPS receiver stations of the International GPS Service for Geodynamics. Stations mentioned in the text have double circles. The global GPS solutions whose timing results are described in the text, use up to 24 stations - such as the set shown circled here.

Figure 2. Maser clock differences between Algonquin and NRC (200 km baseline), obtained from the global GPS solution. Each day is treated independently.

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Figure 3. Maser clock differences between Goldstone and NRC, obtained from the global GPS solution. Some direct common view satellites exist for this 4x10³ km baseline.
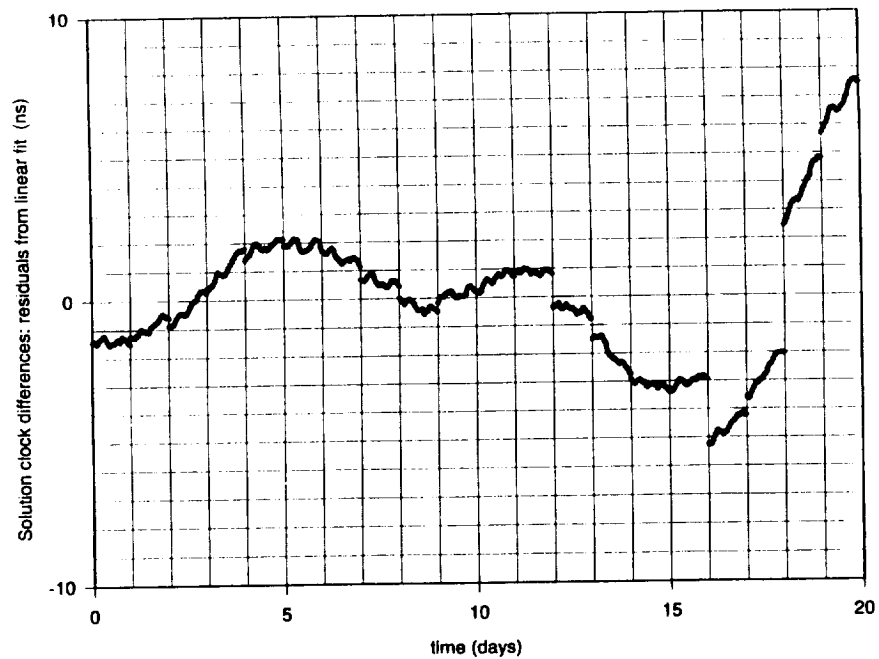
Figure 4. Maser clock differences between Madrid and NRC, obtained from the global GPS solution. Some direct common view satellites exist for this 6x10³ km baseline.
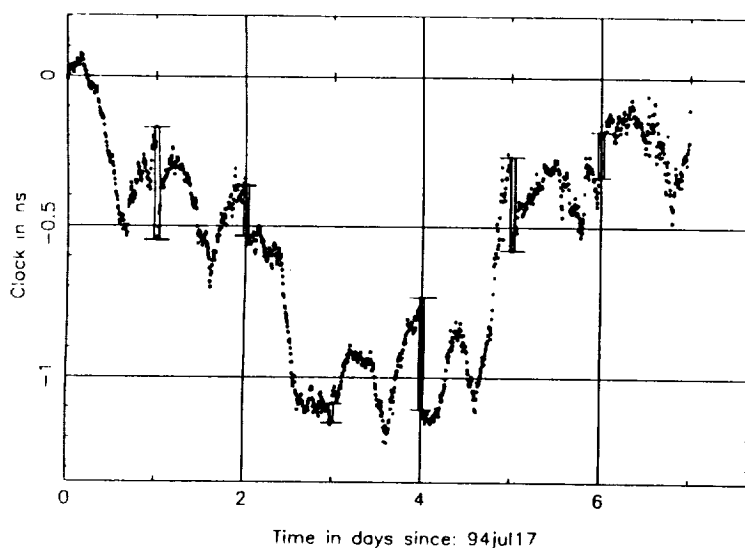
Figure 7. Daily global GPS solutions showing the Algonquin - NRC maser clock differences, with the discontinuities emphasized by the "bars" at 00:00 each day.
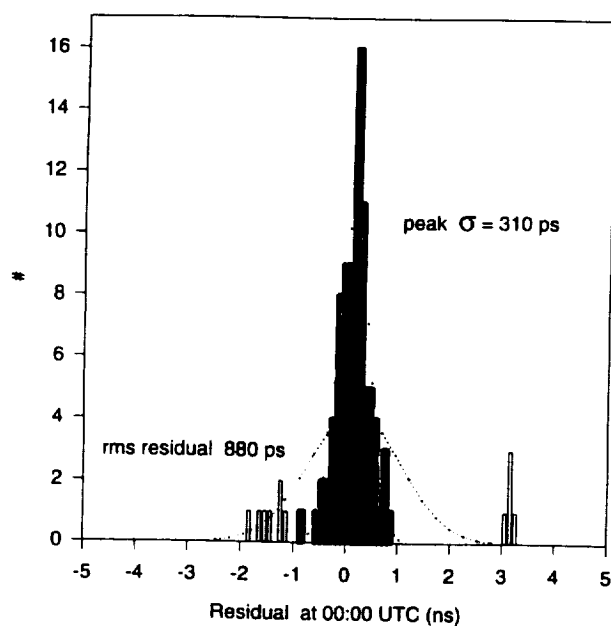

Figure 8. Histogram of daily solution discontinuities for the 20 days of Figs.2-6, between NRC and five IGS stations using masers, scaled by $1/\sqrt{2}$ to reflect the residual at the ends of the daily solutions. The open bars represent values included in the determination of the"rms" value, and excluded from the "peak σ" value.
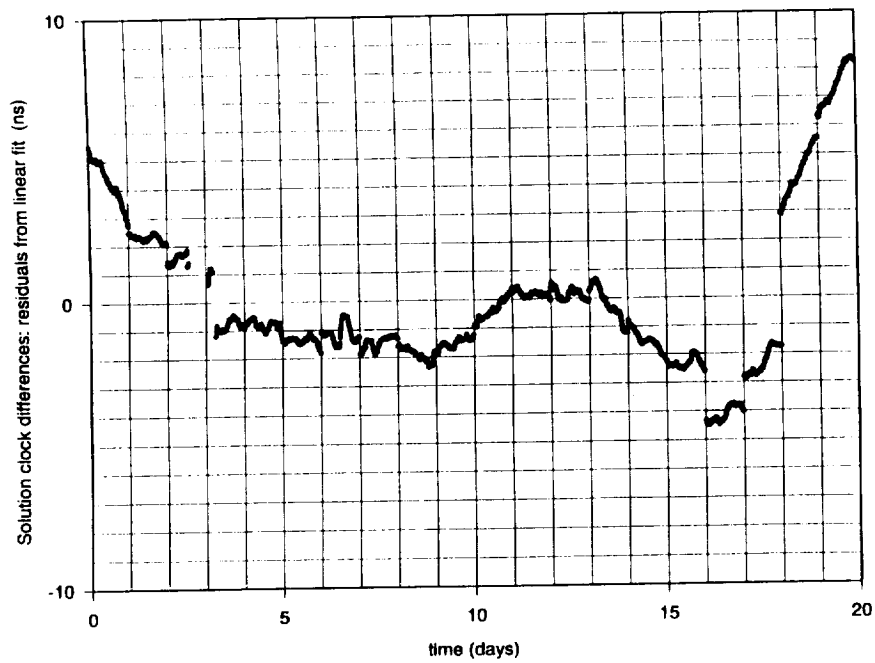
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Figure 5. Maser clock differences between Tidbinbilla and NRC, from the global GPS solution. No common view satellites exist for this 1.7×10^4 km great circle baseline.
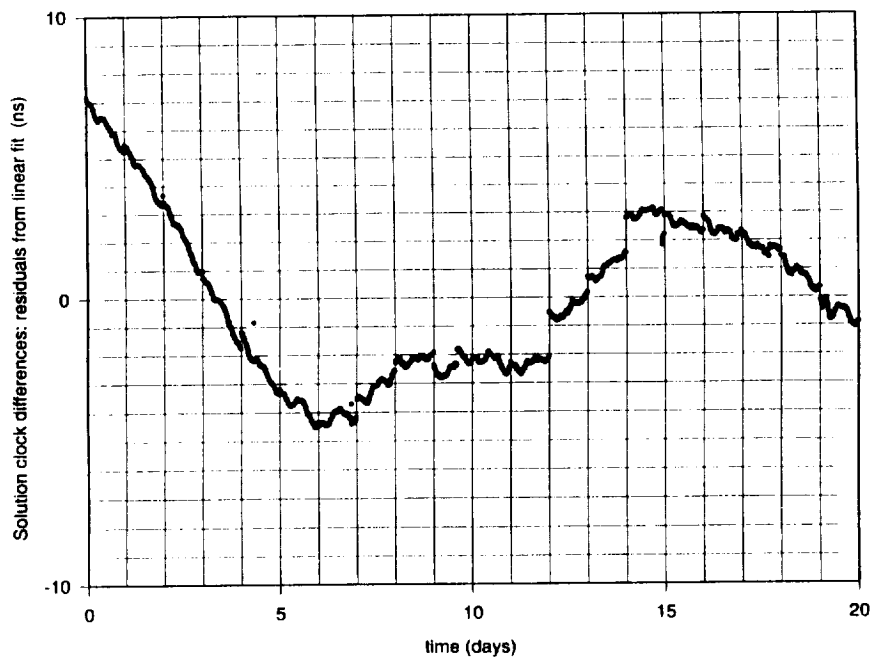

Figure 6. Maser clock differences between Madrid and Goldstone, a 10^4 km baseline.